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INSTRUMENTATION FOR MEASURING PRESSURE WAVES IN GUNS

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The continuous measurement of the pressure difference between the breech and forward ends of a cannon chamber is used by the charge designer to make an evaluation of the ignition process and to determine the existence of pressure waves. The technique of making this measurement involves the analog differencing of two optimally located transducers with a recording system that is properly adjusted, calibrated, and scaled. The resulting differential pressure versus time relationship reveals wave structure that may not be obvious by visual inspection of the two original pressure-time curves.

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I. INTRODUCTION

During the study of interior ballistic phenomena, it is desirable at times to difference two analog pressure signals and display the calibrated output. This technique is particularly useful in the study of propellant charge ignition[1,2]. From the difference of a pressure transducer located in the breech of a gun and one located in the side wall of the chamber near the rear of the projectile (Figure 1), the charge designer can make an evaluation of the ignition process and determine the existence of pressure waves, even if they are of very low amplitude. The resulting differential pressure versus time relationship reveals wave structures that would not be obvious by visual inspection of two original pressure-time curves.

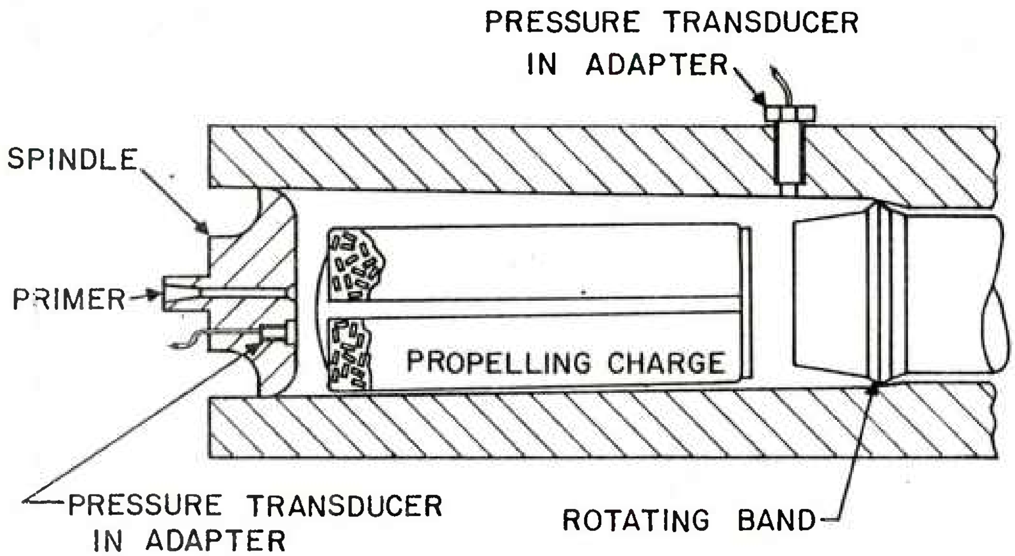

Figure 1. Pressure Transducer Locations

The technique described here is particularly useful when operating in the field where data are recorded on analog magnetic tape and played back at reduced speed on a chart recorder. An initial appraisal of the data can be made on site without the necessity of processing at a data reduction facility.

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[1] *I. W. May, E. V. Clarke, Jr., H. Hassmann, "A Case History: Gun Ignition Related Problems and Solutions for the XM-198 Howitzer," Proceedings of the International Symposium on Gun Propellants, Picatinny Arsenal, 15-19 October 1973.*

[2] *I. W. May, E. V. Clarke, Jr., "The Reverse Chamber Pressure Gradient: A Tool for Assessing the Effects of Wave Dynamics on the Ballistic Performance of Guns," Proceedings of the Second International Symposium on Ballistics, Sponsored by the American Defense Preparedness Association, Daytona Beach, Florida, 9-11 March 1976.*

II. PRESSURE MEASUREMENT TECHNIQUES

A. Basic Pressure Measurement

In order to keep the data reduction process compatible with existing in-house hardware, data reduction programs, and procedures; a standard format[3] is used. This format has five linear calibration steps, each with a 50-millisecond duration, preceding the analog voltage data as shown in Figure 2. When a piezoelectric transducer and charge amplifier[4] are used for making the pressure measurement, the calibration is realized through the charge amplifier calibration port (Figure 3). This input is coupled to the charge amplifier through a built-in 1000-picofarad capacitor and the top step calibration voltage is chosen to induce a charge on this capacitor somewhat greater than the charge that will be generated by the transducer at the maximum expected pressure. The calibration voltage is determined by the relationship:

$$V_c = q_c/C \qquad (1)$$

Where:

V_c = Calibration voltage, top step (volts)

q_c = Charge induced by the top step calibration voltage (picocoulombs)

C = Capacitance of the calibration capacitor (picofarads)

The charge generated by the transducer at an "even" value of pressure somewhat greater than the maximum pressure is:

$$q_t = k\,P_t \qquad (2)$$

Where:

q_t = Charge generated by the transducer at P_t (picocoulombs)

k = Transducer linear calibration constant (picocoulombs/lb/in.^{2})

P_t = Pressure at top calibration step (lb/in.^{2})

$$\text{if: } q_c = q_t$$

$$\text{Then: } V_c = k\,P_t/C \qquad (3)$$

[3] *C.L. Henry, R. L. Martz, E. M. Wineholt, "An Improved Procedure for the Reduction of Interior Ballistic Data Recorded on Analog Tape," Ballistic Research Laboratories Memorandum Report No. 2374, April 1974 (AD#919924L)*

[4] *"Model 504E4 Dual-Mode Amplifier Instruction Manual," Sundstrand Data Control, Inc., Redmond, Washington 98052*

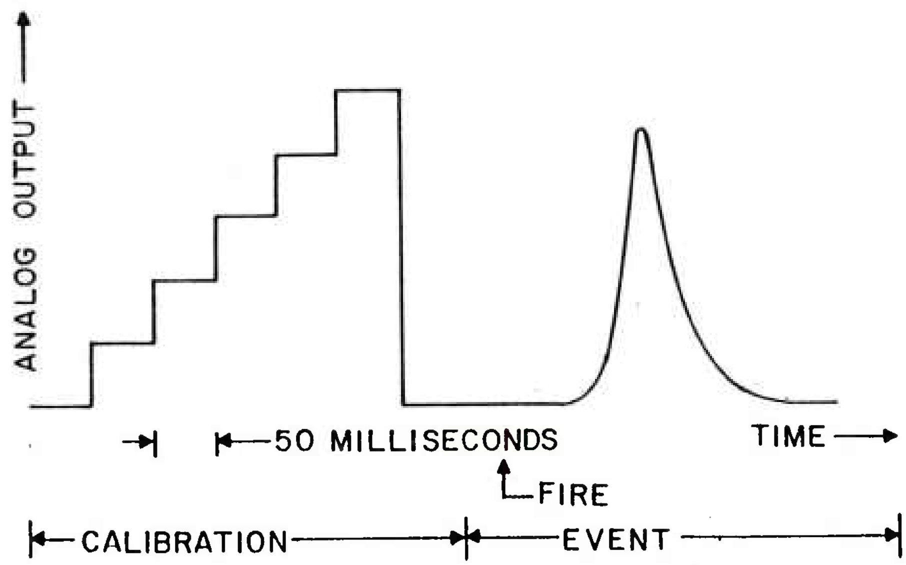

Figure 2. Data Format

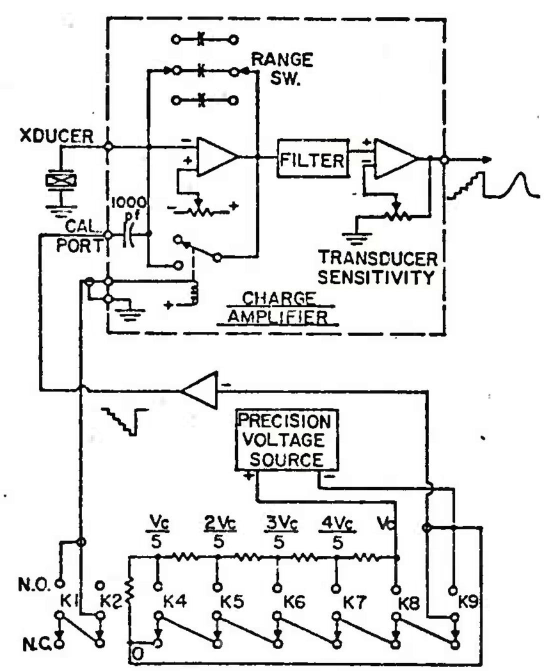

Figure 3. Basic Piezoelectric Pressure Measurement

The charge amplifier's analog voltage output can be adjusted to the desired magnitude with the "range switch" (R) and the "transducer sensitivity" (S) setting[4]. The overall gain of the charge amplifier is the product of R and S, which is set to the desired gain by:

$$RS = kP_t/V_o = V_cC/V_o \tag{4}$$

Where:

R = Charge amplifier range switch setting $(\frac{\text{lb/in.}^2}{\text{volt}})$
(R = 1, 2, 5, 10,.....,5K)

S = Charge amplifier transducer sensitivity setting S = 1 to 11
(picocoulombs/lb/in.^{2})

V_o = Required analog output for P_t (volts)

Note: English units are used here since most commercial charge amplifiers and transducers are calibrated using these units.

Just prior to calibration, the charge amplifier's feedback capacitor is remotely shorted for several milliseconds to eliminate any stray charge. This is done with two relay stages (K_1 and K_2) of a pre-programmed sequence timer. The voltage staircase is generated from a precision voltage source and series connected precision resistors. The pre-programmed sequence timer energizes in sequence the relays (K_4 through K_9) that are connected as shown in Figure 3. An amplifier with unity gain is used to insure that the calibration circuit is not overloaded since it may be used to calibrate more than one amplifier. This is a so-called "end-to-end" calibration and calibrates the entire data circuit with the exception of the transducer.

B. <u>Differential Pressure Measurement</u>

The pressure difference of two analog pressure signals is derived using the system shown in Figure 4. It is important that the paths of the analog signals are identical to avoid errors due to phase shifts and slew rates. The two charge amplifiers (Q_1 and Q_2) use the same calibration and remote short circuits. When selecting the calibration voltage, consideration must be given to the fact that the calibration constants for the transducers may be different and the greater value should be used to calculate the calibration voltage. It is desirable that the transducers have nearly the same parameters and those selected have the most linear outputs. It is necessary that the magnitude of the input voltages (V_1' and V_2') to the differential amplifier (A_3) represent the same pressure magnitude and that they be compatible with the recording device. For an FM channel of a magnetic tape recorder, the required input signal is usually one volt RMS. In this general case it is selected as plus and minus a band edge voltage ($\pm V_E$). To make the analog data from the two transducers compatible, every circuit in the system must be precisely adjusted. Assuming that from the calibration of the selected transducers, pressure (P_{t1}) is greater than pressure (P_{t2}) for the top calibration step. This will serve as a basis for adjusting the various circuits. The output of charge amplifier (Q_1) is adjusted to have

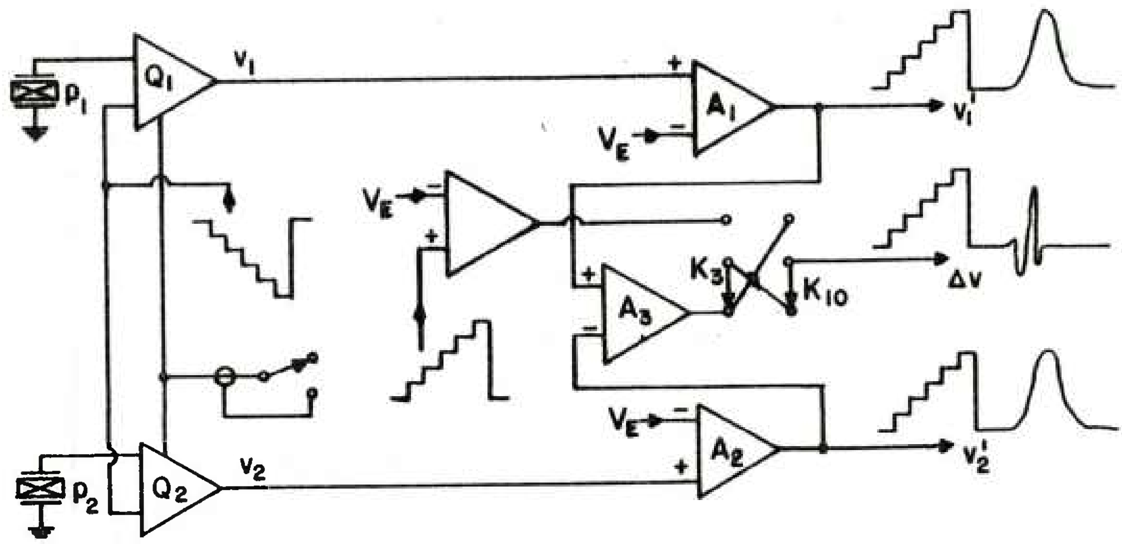

Figure 4. Differential Pressure Measurement

the following values:

@ Calibration baseline

$P_{b_1} = 0 \quad ; \quad V_{b_1} = 0$

@ Top Calibration step

$P_{t_1} = V_c C/k_1 \quad ; \quad V_{t_1} = 2\,V_E$

This is accomplished by calculating the charge amplifier settings (R and S) using Equation (4) with $2V_E$ as the required output for the top calibration step. Several combinations of R and S are possible for each calculated condition. Once the selected R and S combination is set, the output conditions can be monitored while manually operating sequence timer stage K_8 to impress the top calibration step. It may be necessary to adjust the amplifier zero and the transducer sensitivity setting to compensate for dial inaccuracies. The remote short should be activated just before making zero adjustments to remove any stray charge. From the conditions adjusted into Q_1 and assuming that the system is linear, it follows that the relationship of the pressure to the analog voltage is:

$$v = 2V_E(k_1/V_c C)p \tag{5}$$

Where:

v = variable voltage output (volts)
P = variable pressure (lb/in.^{2})

This is graphically depicted in Figure 5 as the linear equation that passes through the point (0,0) and (P_{t_1}, V_{t_1}). Using this relationship and manually operating sequence times stages K_4 through K_9 while observing Q_1 output, the linearity of the system can be determined. Charge amplifier

Q_2 is then adjusted to have the same pressure-voltage relationship as Q_1. It is obvious that the calibration baseline should have the values:

$$P_{b_2} = 0 \quad ; \quad V_{b_2} = 0$$

Using Equations (3) and (5), the top calibration step values are determined as follows:

$$P_{t_2} = V_c C/k_2 \quad ; \quad V_{t_2} = 2V_E(k_1/k_2)$$

This is shown as point (P_{t_2}, V_{t_2}) on figure 5.

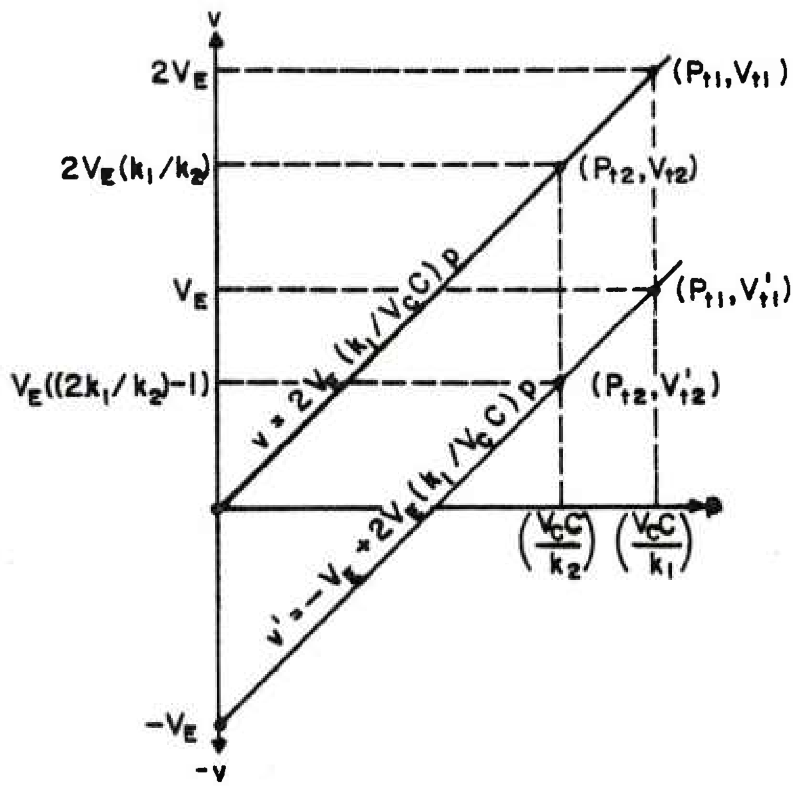

Figure 5. Pressure-Analog Voltage Relationship

Amplifiers A_1 and A_2 should be adjusted for unity gain with the analog signals fed into the non-inverting inputs. A voltage source is fed into the inverting inputs to offset the output by the negative band edge voltage ($-V_E$) for compatibility with the recording device. (On some amplifiers, this function is internally incorporated). The expression for the pressure-voltage relationship at the outputs of A_1 and A_2 is:

$$v' = -V_E + 2V_E\ (k_1/V_c C)p \qquad (6)$$

This relationship is shown graphically on Figure 5. The calibration baseline values for amplifiers A_1 and A_2 are:

$$P_{b_1} = 0 \quad ; \quad V_{b_1} = -V_E$$
$$P_{b_2} = 0 \quad ; \quad V_{b_2} = -V_E$$

Using Equations (3) and (6), the top calibration step values are determined as follows:

$$P_{t_1} = V_c C/K_1 \quad ; \quad V_{t_1} = V_E$$
$$P_{t_2} = V_c C/K_2 \quad ; \quad V_{t_2} = V_E[(2k_1/k_2)-1]$$

The output of differential amplifier A_3 is the analog voltage (Δv) of the differential pressure (Δp). The inputs, in this configuration, are from amplifiers A_1 and A_2, but could have been from Q_1 and Q_2. The former configuration was selected for convenience since the recording system had monitor points at the A_1 and A_2 outputs. This additional rank of amplifiers that the differential signal must pass was insignificant because of the relatively wide bandwidth and fast slew rate of the amplifiers. The analytical expression for the output of A_3 is:

$$\begin{aligned} \Delta v &= G(v_1' - v_2') \\ &= G[2V_E\ (k_1/V_c C)\ (p_1 - p_2)] \qquad (7) \\ &= 2GV_E(k_1/V_c C)\ \Delta p \end{aligned}$$

Where: G = Voltage gain of A_3

To make the differential pressure data consistent with the data format[3], it is necessary that the analog signal be preceded by calibration steps. The signal is interrupted by switching to a voltage staircase during the normal calibration cycle and switching back to the amplifier output when calibration is completed. This is done by two stages of the pre-programmed sequence timer (K_3 and K_{10}). The voltage staircase is generated by a circuit similar to the one that calibrates the charge amplifier and is time-coordinated with it. Baseline ($-V_E$) and top-step voltages ($+V_E$) are adjusted to the same magnitude as the calibration staircase of A_1.

The quiescent state of amplifier (A_3) at zero differential pressures is zero volts and during the dynamic event can swing both positive and negative. This implies that zero pressure does not coincide with the baseline but lies mid-way between the baseline and the top calibration step. This is depicted graphically as Figure 6. Values at the calibration baseline and calibration top step, calculated from Equation 7, are as follows:

$\Delta V_b = -V_E \quad ; \quad \Delta P_b = -\frac{1}{2G_1}(V_c C/k_1)$

@ Top Calibration step

$\Delta V_t = +V_E \quad ; \quad \Delta P_t = \frac{1}{2G_1}(V_c C/k_1)$

Since the analog of the differential pressure is a function of amplifier A_3 gain, it is necessary that the gain be precisely known and that it is adjusted for the expected differential pressure.

III. RESULTS

Typical examples of data acquired using the described techniques are shown in Figures 7 and 8. These data are from experimental propelling charge and igniter configurations. From the Δp versus time plots, the charge designer can evaluate the ignition process as described in References 1 and 2. Figure 7 is an example of a good ignition as evidenced by the normal non-oscillatory positive pressure difference. Figure 8 is an example where abnormal pressure waves exist with the substantial negative pressure gradient indicating poor ignition.

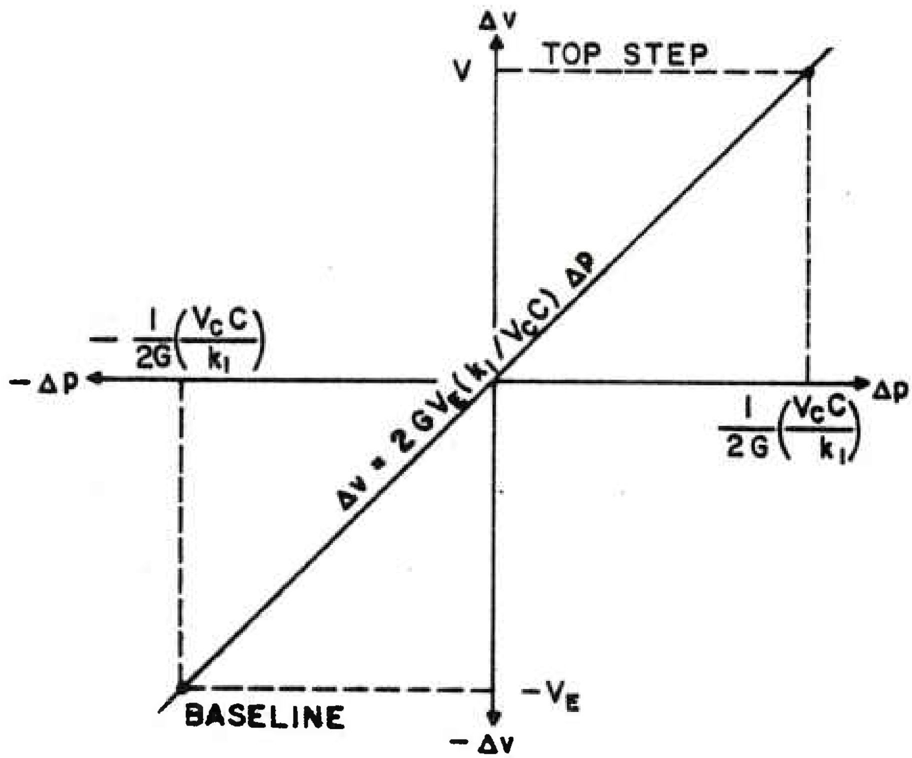

Figure 6. Differential Pressure-Analog Voltage Relationship

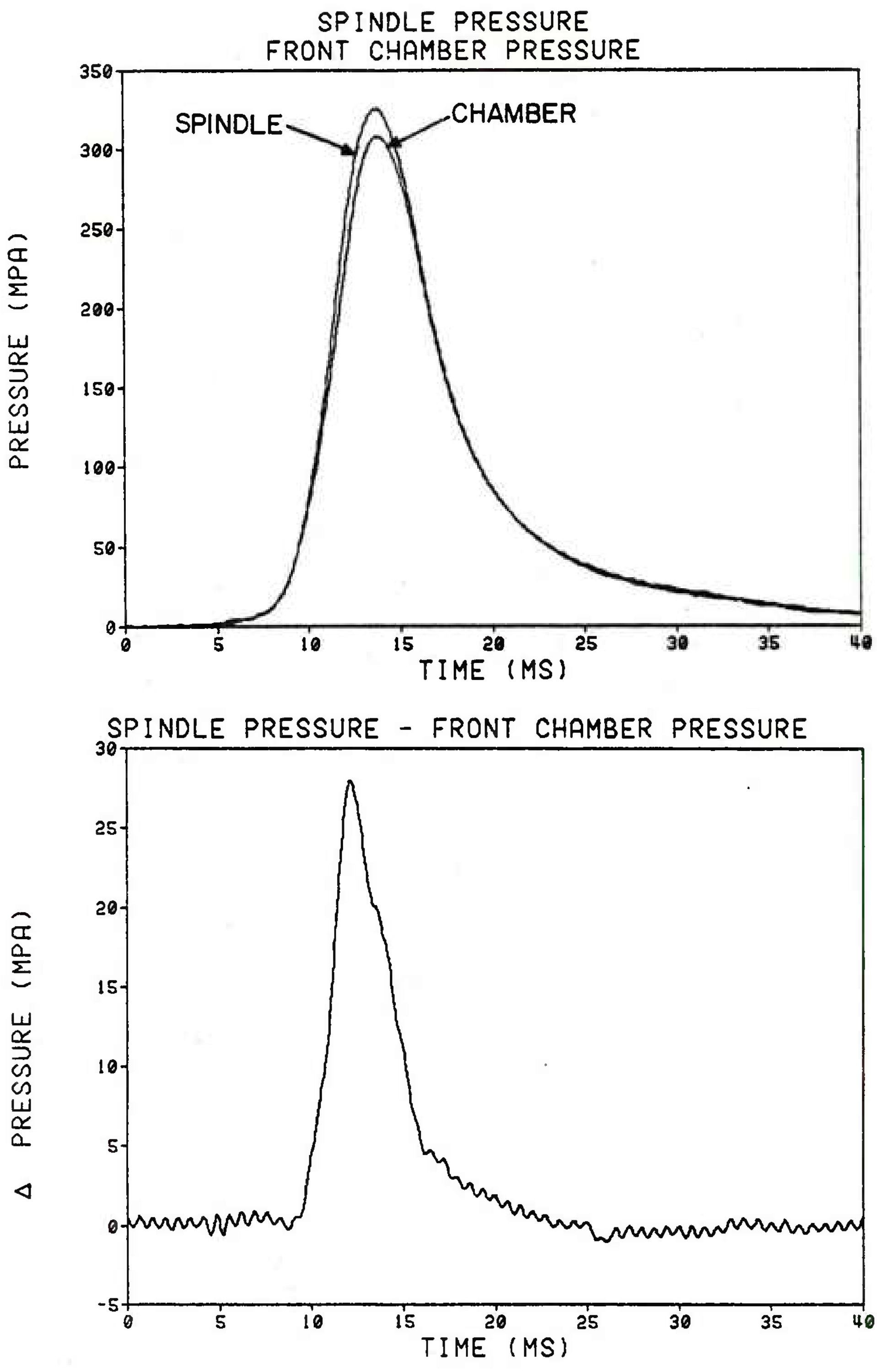

Figure 7. Typical Data, No Pressure Waves

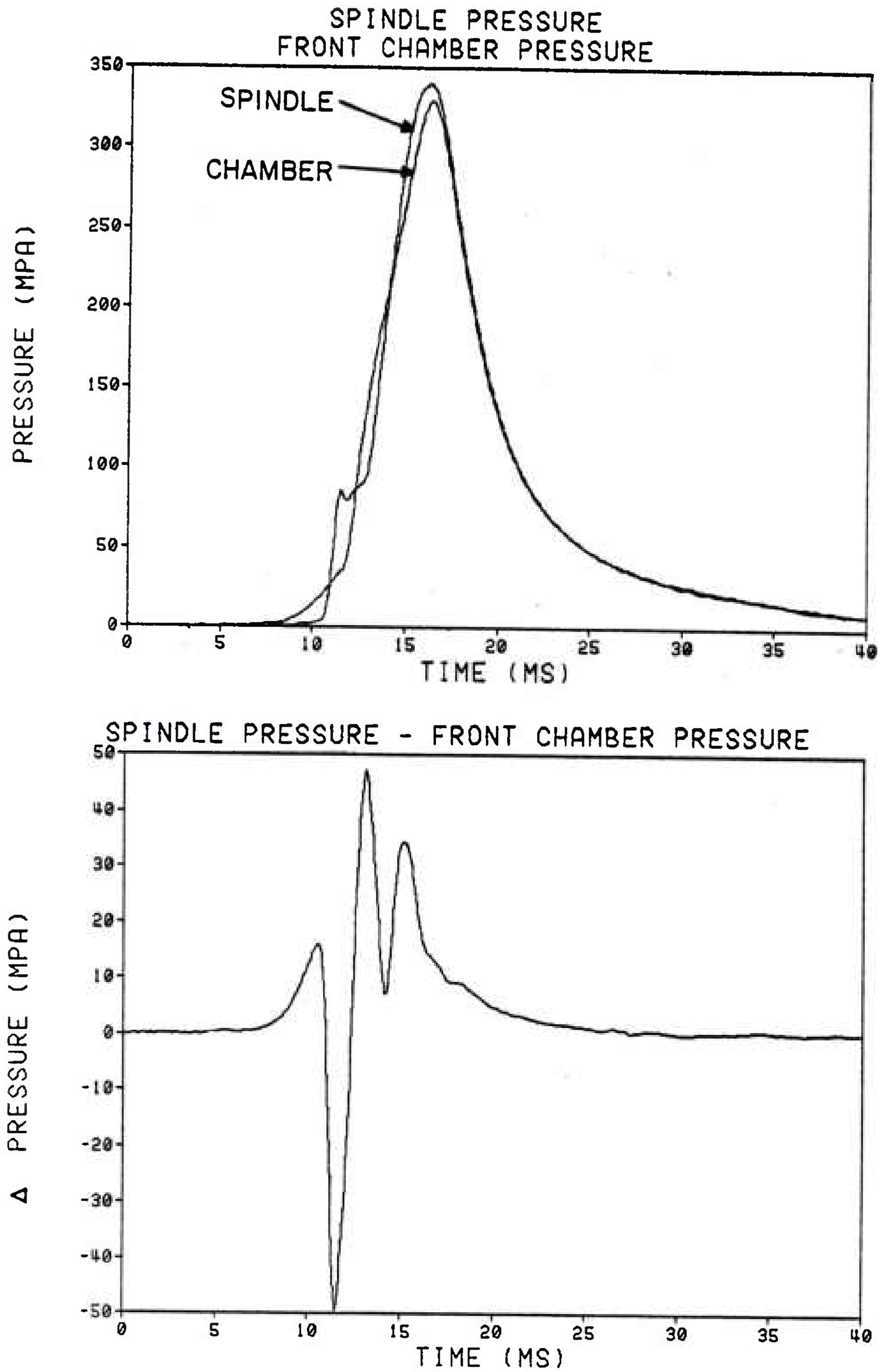

Figure 8. Typical Data, Large Pressure Waves

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